International Research Journal of Multidisciplinary Scope (IRJMS), 2024; 5(3):79-96

Review Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2024.v05i03.01085

Digital Twin in Fluid Power: Review - Uses and Outlook

Akshay Dattaprasad Khamkar, Sudhir Madhav Patil*

Department of Manufacturing Engineering and Industrial Management, COEP Technological University (COEP Tech), Chhatrapati Shivajinagar, Pune: 411005, Maharashtra State, India. *Corresponding Author's Email: smp.prod@coeptech.ac.in

Abstract

Digital Twin (DT) technology is a cutting-edge innovation in Industry 4.0 that combines virtual and physical worlds to create real-time representations of scenarios. Simulation, monitoring, and maximizing efficiency are crucial in industrial automation and have been acquiring significant momentum. Fluid Power Application (FPA) is essential in automation, providing accurate control and significant force through hydraulic and pneumatic systems, fluently merging into current configurations. Although there have been significant improvements in DT technology and its prospective applications in fluid power (FP) systems, there is still a lack of understanding regarding its practical deployment in many sectors. Thus, this study examines the practical applications of DT in FP systems, using the knowledge presented in the previous review papers as a foundation. Although recognizing the importance of emerging DT technology and technological enablers, this study focuses on present FPAs where the adoption of DT is still in its early stages. Further, explores the FP systems usage, and outlines the deployment of DT, including advantages over conventional methods, challenges, and potential implications. Furthermore, the article explicitly outlines the technical challenges. This review study highlights literature gaps and drives DT in FPA's research and developments.

Keywords: Advantages, Challenges, Digital Twin, Fluid Power Applications, Fluid Power Technology, Implementation.

Introduction

FP systems, encompassing hydraulic and pneumatic systems, are essential in numerous fields because of their accuracy, agility, and cost-efficiency. The use of DT technology has the potential to significantly transform these systems by establishing virtual replicates that are firmly interconnected with their real-world counterparts. These virtual copies provide instantaneous sync of data and analysis, providing possibilities for improved control and optimization. The review paper (1), titled "Digital Twin in Fluid Power: Reviewing Constituents" provides a thorough analysis of the essential components of DT in FPAs. These components cover physical and virtual representations, as well as communication frameworks. This entails the creation of precise virtual replicas for the intent of simulations and analyzing, made possible by robust interaction systems. The dynamic nature of DT technology enables predictive modeling and system enhancement, enabling smooth interaction between both real and digital realities. This demonstrates the transformative potential of DT in FP systems (1).

The review article (2), titled "Digital Twin in Fluid Power: Review- Technology Trends" addresses the potential of DT technology in FPAs, with an emphasis on the technological enablers and emerging technologies. The study conducts a systematic literature analysis to identify key aspects that enable the deployment of DT in FP systems. These aspects include virtual blueprints, data fusion, simulation dynamics, control nexus, connective cloud, and sensor insight. Furthermore, the impact of emerging technologies such as artificial intelligence, edge computing, 5G/6G networks, and human-machine interfaces on the progression of DT in FPAs is assessed. DT aims to transform FP systems by taking advantage of these revolutionary developments to improve efficiency, autonomy, predictive capacities, and human engagement. This will ultimately lead to growth and success in the FP operations (2).

This subsequent review paper intends to address the practical application of DT technology in FPAs, enhancing the insights offered by preceding review papers (1, 2). The present article strives to simplify

(Received 08th May 2024; Accepted 15th July 2024; Published 30th July 2024)

the current uses of FP that have not yet incorporated DT, examining possibilities for integration, associated benefits, difficulties, and potential consequences. This study seeks to bridge the disparity between theoretical comprehension and practical implementation by analyzing case studies and assessing the components, roles, pertinent technologies, and technical obstacles of DT. This review paper tries to analyze the utilization of DT in FP systems in order to gain an improved comprehension of how it might improve system efficiency, autonomy, and predictive capacities. It also highlights areas that require more research and development. The purpose of this work is to present and investigate seven review issues that were obtained following an exhaustive analysis of a collection of previously published research. (1) What does DT stand for? (2) What is FP technology? (3) What are the present applications of FP systems and how can DT be applied in these applications? (4) What are the existing FP systems that incorporate DT technology? (5) What are the primary obstacles in executing DT for FPA?

Fluid Power Technology Overview

FP Systems, encompassing both hydraulics and pneumatics, are essential components in several industries, that use pressurized fluids to exert force and regulate motion. Derived from Pascal's rules, these systems have undergone centuries of development to provide energy for a wide range of industrial purposes. Hydraulic systems, prevalent in heavy industries, employ oil as a medium to transmit power via three primary components: a pump, valves, and actuators (3). They demonstrate exceptional power density, force generation, and efficiency in linear motion. Technological progress following World War I resulted in the development of hydraulic valves that allowed for accurate control over flow, pressure, and the operation of actuators (4). The article centers on the process of modernizing by implementing electro-hydraulic valves. It investigates enhancements in sensors, controllers, and communication systems to ensure readiness for Industry 4.0 (4). Pneumatic systems, which employ compressed air or gases, provide clean and lightweight solutions, particularly advantageous in the manufacturing sector (5). The essential elements comprise compressed air sources, cylinders, valves, and filters. Due to their natural ability to adapt and their ability to change stiffness, they are becoming more widely used in medical applications. Advanced control techniques are used to handle the inherent nonlinearity (5). On the other hand, electro-pneumatic systems use programmable logic controllers (PLC), pneumatic actuators, and electric controls. The study explores operational leads for Industry 4.0 adaptability without software modification and PLC programming standards (6).

The paper highlights challenges with traditional hydraulic systems, prompting the emergence of power-by-wire alternatives like Electro-hydrostatic Actuators (EHA) and Electromechanical Actuators (EMA). EHAs integrate motors and pumps within hydraulic actuators, while EMAs directly convert electric power to motion, offering weight reductions and improved reliability for aircraft (7). The work addresses digital hydraulic systems, which utilize discrete signals to intelligently regulate fluid flow (8). By incorporating digital valves, pumps, and cylinders, these systems provide enhanced efficiency and resilience in comparison to conventional ones. Ongoing research endeavors encompass a wide range of areas, including component design, modeling, control systems, energy efficiency, and integration (9, 10). This extensive examination shows scholarly attention to understanding FP technology's complicated elements. As illustrated by Figure 1, FP technology is vital for construction machines, aviation, and manufacturing. This shows the technology's adaptability and significance (11). This study goes beyond general overviews to examine specialized and innovative areas of the work. The study explores specific topics such as hydraulic quadruped robots (12) and EHAs in aircraft (7), emphasizing the importance of FP in the movement and control of locomotion and flight surfaces. The paper addresses hydro-pneumatic accumulators, with a focus on energy storage options (13) and advanced control methods for pneumatic systems (14). These observations collectively demonstrate the changing terrain of FP technology. The review incorporates these observations to emphasize FP systems' continued evolution and vital role in modern industrial energy (14, 15). This detailed study will be useful for practitioners interested in engineering complexity and breakthroughs, particularly in FPAs. An approach referred to as the systematic literature review (SLR) normally consists of the following phases: preparing the literature review, implementing the literature review, and interpreting and delivering the information (16). Therefore, in order to carry out the studies for the current review, these steps are followed.

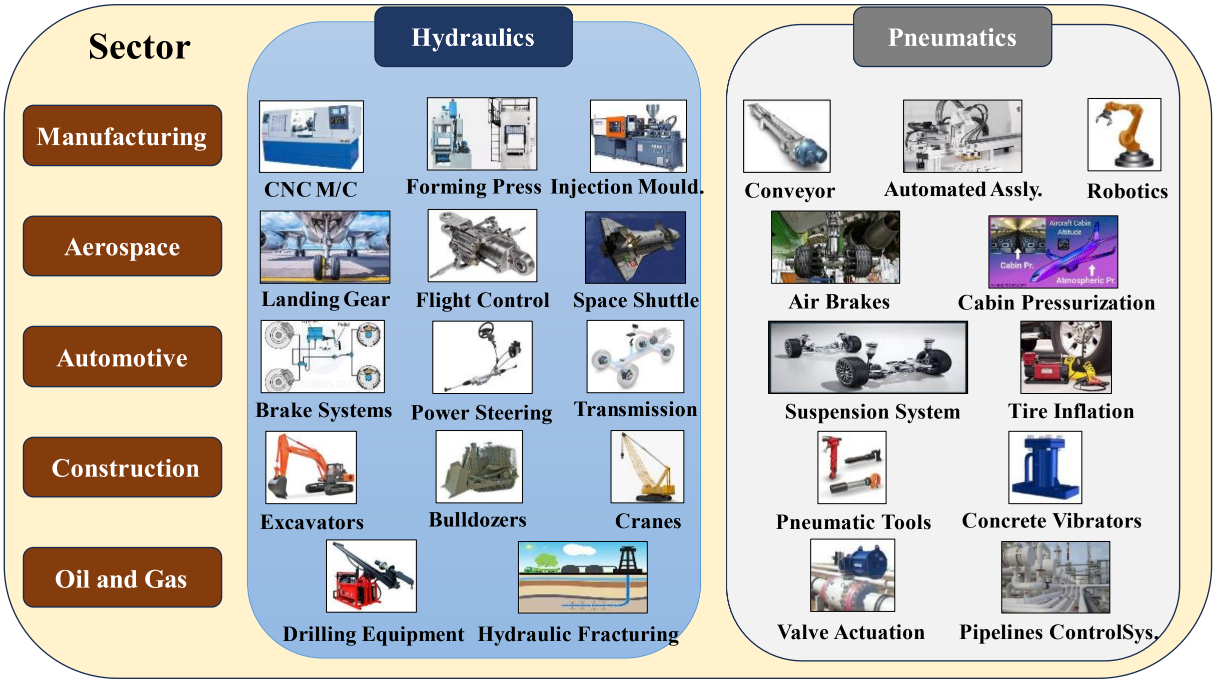

Figure 1: Applications of Fluid Power in Various Sectors

Significance of Digital Twin in Fluid Power Applications

The importance of DT technology in developing fluid power systems is evident since it provides capabilities that go beyond conventional monitoring and control. Digital twin offer a precise and real-time digital representation of physical systems by combining sensors, data analytics, and machine learning algorithms. This technological progress enables the use of dynamic simulations and predictive analytics, which are essential for optimizing the performance and reliability of fluid power systems. The theoretical underpinnings of digital twin technology highlight its function as a revolutionary tool for connecting the physical and virtual domains. The foundations of these models are built on advanced mathematical algorithms that precisely replicate the functioning of fluid power elements and systems. These models provide valuable insights into intricate dynamics and facilitate well-informed decision-making by integrating real-time data (1).

In the dynamic realm of Industry 4.0, digital twin are acknowledged as groundbreaking ideas, especially in the domain of fluid power systems where accuracy and effectiveness are of utmost importance. Digital twin enable the improvement of industrial processes by boosting visualization, analysis, and prediction capabilities. This leads to preventive maintenance, predictive modeling, and functional optimization. This review seeks to enhance the comprehension of digital twin principles in relation to fluid power technology by consolidating their theoretical foundations and practical implementations.

Discussion

The discussion part provides a comprehensive analysis of the present applications, technical challenges, and areas of research that need to be addressed in relation to DT in FPAs. An investigation is carried out on the resources that were published between the years 2000 and 2023. This investigation covers a wide range of source forms, including journal papers, conference papers, and book series. Some of the search terms that were included in the articles were "Digital Twin," "Fluid Power Systems," "Fluid Power Application," "Hydraulic Systems," "Pneumatics Systems," "Applications," "Challenges," "Future Directions," "Implementation," and "Manufacturing," among others. In each section of the papers, these terms were joined by a process of selective combination. Figure 2 can discover the comprehensive index that may be used to conduct in-depth literature searches in academic databases. Over 200 articles from the literature have been subjected to a thorough analysis based on the rating of their degrees of relevance. There are 58 publications that have been chosen for inclusion in the Mendeley database for the purpose of conducting in-depth reading and analysis. These papers are extremely pertinent to the objective of the review. A number of different aspects are covered in these articles, including the title, the abstract, the introduction, the applications, the challenges, the future directions, and the conclusion. For the purpose of narrowing down the specific research field that this review will be focusing on, the study concentrates on the documents that have been chosen for the database that are restricted to the domain of "fluid power applications" during the phase of literature screening.

Fluid Power Applications

As outlined below, this thorough study explores hydraulic and pneumatic FP system applications in numerous industrial areas. This section shows the importance of FP systems in many ways through numerous applications. However, DT technology has not yet been used to improve these systems. This section discusses DT implementation in the described applications. It examines the DT's advantages over existing systems, potential implementation issues, and predicted outcomes.

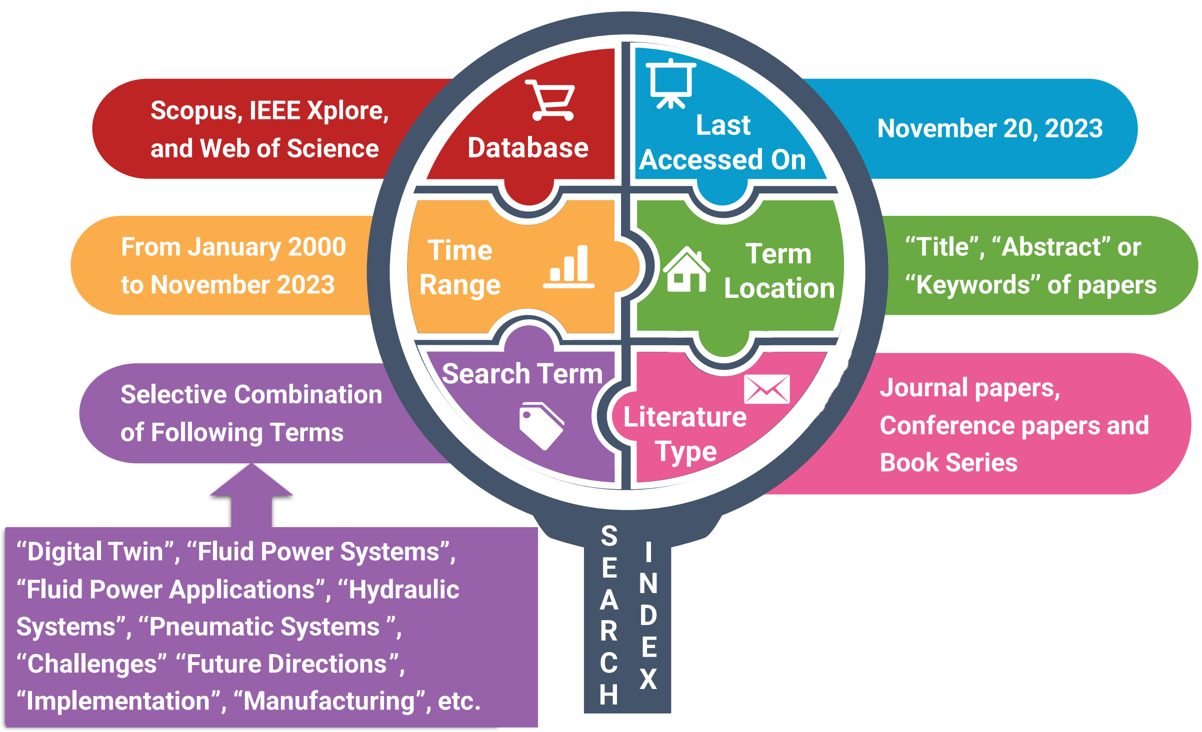

Figure 2: Literature Search Content: Academic Database

Industrial earthmovers: The discussion begins with robust earthmoving equipment, where hydraulic systems are dominant. The study focuses on valve-controlled hydraulic systems, actuators, pumps, and energy recovery technologies. This research highlights hydraulic systems' performance in heavy machinery and their importance in control and energy efficiency (17).

Mobile robot: The study uses strong hydraulic and pneumatic technologies to overcome mobile robot height limits. Pneumatic spiral lift actuators modify height and permit leg mobility. This technology allows the robotic system to navigate diverse landscapes and overcome obstacles, showcasing FPA's extraordinary dexterity and versatility (18).

Flight control: The next portion of the examination addresses a major aviation change: airplane actuators switching from hydraulic to electrical systems. The concentration on EHAs and EMAs indicates a noteworthy shift toward electric aviation technologies. This shift emphasizes efficiency improvements and shows how aerospace engineering FPAs are changing (19). The aircraft industry has the potential to greatly benefit from the integration of DT into FP systems. These sophisticated models enable precise monitoring and analysis of FP systems utilized in airplanes, guaranteeing optimal performance and safety. DT provides proactive maintenance, mitigating the possibility of in-flight malfunctions and decreasing maintenance expenses. Additionally, they provide the simulation of highly challenging operational situations, hence assisting in the development and evaluation of resilient systems. Through the integration of DT, the aerospace sector may improve the dependability, effectiveness, and security of its FP systems, ultimately leading to the development of more sophisticated and robust aircraft designs.

Braking system: This study mathematically models and experimentally validates a passenger car hydraulic braking system, underlining the automotive industry's importance. Hydraulic circuits, tandem master cylinders, brake calipers, and valves are thoroughly examined. The importance of FP and validation emphasizes hydraulic systems' role in reliable and effective car brakes (20). FP systems in the automobile sector can be significantly transformed by the implementation of DT. They provide accurate simulations and testing of hydraulic and pneumatic components, hence improving the design and development process. Utilizing DT, predictive maintenance guarantees the dependability and durability of these systems, hence minimizing the likelihood of failures and their associated expenses. Furthermore, DT facilitates the enhancement of fuel efficiency and emissions control, coinciding with the industry's commitment to adopting more environmentally friendly technologies. Through the utilization of DT, automobile makers can attain elevated performance benchmarks, enhance vehicle safety, and expedite advancements in FPAs.

Agricultural machinery: Tractors use hydraulic systems for steering and propulsion, as shown by agricultural machines. This article investigates hydraulic systems' complexity, including variable displacement pumps, directional control valve blocks, and proportional solenoid valves. This study examines hydraulic systems used to give agricultural machinery better steering modeling and control issues (21).

Workpiece turnover: Industrial automation is the subsequent section of the study, which introduces a hydraulic system for regulating a workpiece turnover mechanism in an automated manufacturing line. To create a complete system, pumps, valves, cylinders, and reservoirs are carefully interconnected. A PLC for electrical control shows how FP and automation work together in industrial settings (22).

Injection moulding: Further research shows that injection moulding machines use a sophisticated servo-hydraulic system to imitate filling and packing. Using a Proportional-Integral-Derivative (PID) controller and a thorough assessment approach, injection moulding machine hydraulic systems can achieve accuracy and regulation (23).

Tube bender: The next topic focuses on energy efficiency, specifically hydraulic tube bender design to save energy. The use of an internal gear pump and AC servomotor shows how hydraulic systems can reduce energy usage, highlighting the vitality of FP in sustainable production (24).

AUV docking: The study shows how a hydraulic system docks a multi-freedom autonomous underwater vehicle (AUV). The hydraulic system controls shaft locking, heading angle, roll angle, pitch angle, AUV locking, and charging. It is built for the harsh deep-sea environment (25).

Industrial – gripper: In industrial automation, pneumatic gripper devices are utilized for pick and place. Compressed air can operate cylinders and valves quickly, cleanly, and cost-effectively in industrial applications (26).

Adaptive-clamping CNC: Industrial automation continues with Smart Clamping Force Control. This electro-pneumatic system clamps and unclamps workpieces on a CNC machine tool using pneumatic components. The seamless integration of pneumatic components with electrical control systems shows FP's versatility and efficiency in industrial automation (27). The implementation of DT in FP systems has substantial ramifications for the industrial sector. Utilizing DT allows for continuous monitoring and proactive maintenance, resulting in decreased periods of inactivity and improved operational effectiveness. Through the process of simulating and analyzing the performance of their FP systems, organizations can enhance the efficiency of these systems, leading to reduced energy consumption and improved productivity. In addition, DT enhances decision-making by offering extensive data insights, enabling firms to foresee and resolve possible difficulties before they worsen. This technical innovation is positioned to completely transform industrial operations, enhancing their efficiency, cost-effectiveness, and sustainability.

Locomotive system: The study paper then discusses locomotives and gives a one-dimensional pneumatic and brake system virtual model. The screw compressor unit, compressed air-drying package unit, brake cylinders, pipelines, reservoirs, and control valves are meticulously modelled in this pneumatic system model. The importance of energy economy and speed criteria emphasizes the pneumatic system's role in modern train braking (28).

Conveyor robot: In industrial automation, conveyor robot systems use pneumatic systems to grip and manipulate things. Pneumatic systems use compressed air as their power source. These systems require a compressor, air tank, pneumatic cylinders, solenoid valves, and sensors. These parts form the pneumatic circuit. Pneumatic systems are suitable for industrial automation due to their speed, cleanliness, affordability, and ease of maintenance (29).

Lift-assist manipulator: The following section discusses the importance of the lift-assist pneumatic manipulator. The pneumatic system's double-acting cylinder provides manipulator lifting power. Pneumatic systems in material handling can achieve great accuracy and flexibility by using a control strategy and dynamic air pressure changes (30).

Boxes sorting machine: This paper concludes by discussing the importance of automated sorting in packing and the use of pneumatic systems in carton box sorting machines. In industrial automation, pneumatic cylinders and direction control valves are used to classify carton boxes by size, focusing on cost-effectiveness and productivity gains (31).

This extensive review paper discusses hydraulic and pneumatic system's widespread and important uses in numerous sectors. FP is essential in heavy equipment, robotics, aerospace, automobile, renewable energy, and industrial automation. These systems underpin technical advancement, operational efficiency, and innovation. However, DT technology is being investigated to improve these systems. This section summarizes DT deployment in the described applications as shown in Table 1.

Table 1: Potential of DT Concept in Current FPAs

Application	Digital Twin Implementation	Advantages Over Traditional Approaches	Challenges	Potential Implications
Industrial Earthmovers (17)	Real-time monitoring and control using sensor data	Improved predictive maintenance, enhanced efficiency	Complex data security and integration	Reduced downtime, improved performance
Mobile Robot (18)	Virtual hydraulic system dynamics simulation	Better design validation, cheaper prototyping	Calibration and model correctness	Increased adaptability, navigation precision
Flight Control (19)	Real-time electro-hydrostatic actuator monitoring	Reduced weight, improved reliability	Synchronization and latency difficulties	More electric airplane, safer
Braking System (20)	Brake system digital representation	Improved anti-lock braking algorithms, faster response	Cybersecurity, system integration	Increased safety, better braking
Agricultural Machinery (21)	Variable-condition hydraulic system simulation	Improved mobility and handling over difficult terrain	Validation and model correctness	Increased productivity, precise guiding
Workpiece Turnover (22)	Automated process digital simulation	Best control, shorter cycle time	Integration with current systems	Automation boosts production efficiency
Injection Moulding (23)	Simulation of filling and packing in real time	Precise control, energy savings	Model precision and computational load	Improved injection molding research, energy-efficient designs
Tube Bender (24)	AC servomotor and internal gear pump digital representation	Precision flow and pressure control, energy savings	Systems' complexity and integration	Energy-efficient tube bending, greener
AUV Docking (25)	Real-time hydraulic control simulation for multi-freedom device	Greater control and adaptability	Latency and communication issues	More efficient deep-sea operations, less manual intervention
Industrial – Gripper (26)	Pneumatic gripper system digital representation	Quicker, more adaptable pick-and-place operations	Calibration and model correctness	Cost-effective industrial automation, efficiency gains
Adaptive-Clamping CNC (27)	Electro-pneumatic clamping system DT implementation	Real-time clamping force adjustment	Integration with current systems	CNC tool clamping improved, and mistakes decreased.

Locomotive System (28)	Real-time pneumatic and brake simulation	Simulated workflow, component optimization	Model precision and computational load	Improved locomotive braking safety and efficiency
Conveyor Robot (29)	Pneumatic cylinder and valve DT implementation	Fast, clean, and cheap motion control	Model precision and computational load	Effective pick-and-place robots, automation
Lift-Assist Manipulator (30)	Lift-assist double-acting cylinder simulation in real time	Ideal air pressure for lifting, reduced balancing errors	Strategic control and calibration	Reduced lifting errors, improved performance
Boxes Sorting Machine (31)	Virtual pneumatic cylinder and direction control valve simulation	Cost-effective and flexible sorting	Calibration and model correctness	Improved carton box sorting, industrial automation

Digital Twin in Fluid Power Applications

DT have become prominent and influential tools in the domain of FPAs, providing versatile applications that encompass various aspects like design, operations, and maintenance. The complete review study emphasizes the exploration of the exploitation of hydraulic and pneumatic components and systems in relation to the DT, demonstrating the extensive range of their impact on numerous aspects.

Manufacturing and mechatronics: This research highlights the significant importance of digital twins as a valuable tool for simulating and optimizing complex interactions among various components, such as pumps, valves, and other elements, inside fluid power systems. The statement underscores their proficiency in enhancing the efficiency of fluid power applications while offering immediate data for cost reduction and comprehensive process understanding. This technology thoroughly examines and verifies control programs throughout the development process, thereby preventing collisions and damage during physical testing. Performing parameter analysis at an early stage enables the optimization of machine design by considering the complexity of simulations. Continuous monitoring facilitates the use of data to predict maintenance needs, hence improving productivity and optimizing maintenance schedules. DT simulations mitigate the possibility of human mistakes during physical testing, ensuring control program and design verification are error-free. DT streamlines the handling of extensive quantities of sensor and operational data in intricate systems, resulting in cost savings and rendering them indispensable for mechanical, mechatronic, and manufacturing applications (32).

Educational-development workplace: This study emphasizes the importance of Unity and OPC UA in FP system DT development. This integration allows virtual simulation and visualization of hydraulic and pneumatic components and their complex linkages (33).

Production line: The educational platform-specific Game Automation Framework is software. The Game Automation framework is used to implement DT in FPAs in this document. The platform emphasizes bidirectional communication and interactivity, making it useful for hands-on learning in design creation, performance testing, and predictive maintenance (34).

Hydraulic system - detecting leaks: The study presents a compelling instance of a digital twin of a hydraulic system that is specifically designed for leak diagnosis applications. The combination of real-time data with Internet of Things (IoT) technologies demonstrates the promise for enhanced monitoring, control, and accurate diagnosis of hydraulic systems, specifically within water distribution networks. By providing remote monitoring and control capabilities, this technology enables real-time simulations that are synchronized with sensor readings, making it easier to discover anomalies. The DT structure facilitates remote online leak diagnosis using a genetic algorithm. Intuitive interfaces facilitate the ability to control systems from a distance and visually observe the outcomes of diagnostic tests. Analytical capabilities, such as consumption pattern analysis and predictive maintenance, can be facilitated by storing historical data in the cloud. The modular design guarantees the potential to scale up, allowing the DT concept to be easily adjusted for larger sections of water networks or entire districts (35).

Rolling mill coilers: This study examines producing and using DT aggregates in mechatronic rolling mill complexes. This study discusses using DT to prototype electromechanical and hydraulic systems, emphasizing virtual commissioning and exact modeling to improve design and performance (36).

Closed hydraulic system - linear actuator: The authors put out a proposition for a condition monitoring technique for a hydraulic system, which is driven by data and relies on the utilization of a digital twin. This strategy showcases adaptability and scalability by employing simulation models and minimizing the necessity for long test runs. Consequently, it offers a potential technique for quick defect identification and maintenance. It enabled the creation of abundant training data for machine learning models, effectively replicating the hydraulic system under different failure scenarios. The training data for the DT encompassed both typical and distinct failure types, which are essential for supervised ML methods. This methodology necessitated a reduced number of practical trial iterations after the creation of the model, hence preserving valuable resources. The DT's flexibility in accommodating system design modifications facilitated seamless software updates, in contrast to the difficulties associated with gathering fresh real-world data. Furthermore, the utilization of DT technology allows for the simulation of challenging, hazardous, or unachievable failure scenarios, hence expanding the scope of detectable flaws (37).

Predictive maintenance and fault diagnostics: This case study uses DT models for hydraulic system defect diagnosis and predictive maintenance. This work uses virtual representations to solve defect identification and maintenance problems, displaying improved precision and flexibility (38). DT has the potential to greatly enhance the effectiveness of predictive maintenance in fluid power applications. DT can monitor system performance and spot anomalies early by producing a real-time virtual replica of the hydraulic system. This feature allows for the anticipation of possible malfunctions prior to them causing system breakdowns, enabling prompt and focused maintenance interventions. DT improves fault diagnosis accuracy by utilizing simulation data and historical fault data, resulting in decreased unexpected downtimes and maintenance expenses. Implementing this proactive maintenance strategy not only increases the longevity of hydraulic components but also guarantees excellent system dependability and safety.

Energy efficiency - hydraulic systems: This study uses a DT to evaluate hydraulic system energy-saving strategies in real-time using the modular approach. The present approach involves automated inefficiency detection, operator engagement in implementation, and a major goal of improving hydraulic system energy efficiency and cost reduction (39).

Advanced physics-based modelling: The paper focuses on smart manufacturing, but its methodologies can help us understand DT in FPAs. Complex physics-based models are the initial step to building DT, which allow planned maintenance and communication between virtual and actual systems (40).

Practical training system: A study on smart production and practical training systems suggests DT uses in FPAs. DT are excellent for training, mimicking, and increasing performance because they provide a controlled virtual space for knowledge and performance (41).

Engine block manufacturing processes: Manufacturing system literature describes DT as improving FP efficiency and dependability. Remote monitoring tracks fluid pressure and valve locations. Predictive analysis helps discover and resolve bottlenecks with real-time data integration. DT security techniques in manufacturing can protect FP systems against cyberattacks, maintaining their functionality and security (42).

Smart manufacturing systems: PLC-influenced DT enhances FP system efficiency and integration. They simulate hydraulic components for real-world performance. This streamlines assembly and integration for industrial internet monitoring and control. Closed control loop DT improve semi-physical simulation models for FP process evaluation and optimization before implementation (43).

Mechatronic system: PLCs can improve FP system management, monitoring, and optimization using DT. Bidirectional data interchange between the DT and hydraulic or pneumatic systems allows virtual control technique testing, enhancement, and validation (44). Utilizing DT in FPAs enables sophisticated mechatronics system optimization. DT offers a comprehensive and dynamic perspective of the entire FP system, allowing for deep analysis and real-time monitoring. Engineers have the ability to replicate different operational situations and detect inefficiencies inside the system, enabling them to make accurate modifications and enhancements. This iterative optimization technique improves system performance by adjusting settings, minimizing energy usage, and ensuring optimal system operation. As a result, DT plays a role in increasing productivity and promoting sustainable operations in fluid power applications.

Automation line: The paper explores DT technology in higher education and suggests using it to educate FP systems. DT allows students to undertake online laboratory experiments that mimic real-world industrial processes. This offers new ways to teach and study FP systems (45).

Geothermal drilling system: DTs are used in geothermal drilling, and their use in FP systems is worth investigating. DT can simulate hydraulic and pneumatic components for real-time monitoring, control, and troubleshooting, improving efficiency and dependability (46). DT greatly enhances overall efficiency in fluid power applications by closing the gap between the physical and virtual domains. They provide the smooth incorporation of real-time data with sophisticated analytics and machine learning algorithms, offering a strong foundation for making decisions based on data. This comprehensive approach guarantees that every component of the FP system, including design, testing, operation, and maintenance, is optimized to achieve maximum efficiency. The utilization of DT enables a seamless feedback loop, enabling swift adaptation to evolving circumstances and prompt execution of remedial measures. Consequently, fluid power systems exhibit more adaptability, resilience, and efficiency, resulting in improved productivity and decreased operational expenses.

Elevator security system: The study uses analogies to explain developing a Digital Triplet for FP systems. To accomplish this, use Siemens NX to create a virtual model and connect it to a PLC-controlled physical model. Through two-way communication, OPC-UA allows FP system monitoring, decision-making, and problem identification in real time (47).

Parallel robot controlled: In FP applications, DT streamlines planning and commissioning. DT are living models that collect IoT sensor data in real-time, like parallel robots. Testing, visualizing, and tuning hydraulic and pneumatic parts remotely with this virtual model speeds up development and commissioning (48).

Machine tool: This study suggests applying CNC machine ideas to FP systems. DT create virtual models that precisely simulate and validate hydraulic and pneumatic components before real-world installation. Real-time data integration and visualization technologies help analyze FPA performance and future trends (49).

Reconfigurable assembly system: The paper highlighting the significance of physical modeling-based DT in providing a virtual testbed for enhancing the design, operations, and maintenance of intricate real-world FPAs. DT provide a complete and detailed model of the full FP system. They allow for system-level simulations, exploration of design possibilities, and optimization of hydraulic circuits to enhance efficiency (50).

Material handling system: Studying how to create a digital simulation of a material handling system can be applied to FP applications. The simultaneous interaction between the digital replica and the physical system improves data-driven decision-making, displaying industrial technique applications (51).

The review paper provides a comprehensive analysis of DT applications in FPAs, demonstrating their transformative potential in several domains. Table 2 provides a concise overview of the specified applications in terms of their relationship to DT components, the role of DT, and the key technologies involved. They have developed a novel method to enhance efficiency, ensure reliability, and facilitate research and teaching in the domains of FP technology.

Table 2: Comprehensive Literature Review of DT in FPA

Case Study	DT Components	Role of DT	Key Technology	Summary
Manufacturing and Mechatronics (32)	Pump, valves, and elements simulation	Simulation, interface refinement, performance optimization	Unity (3D), OPC UA, SQL Server	DT technology improves hydraulic and pneumatic process efficiency and reliability
Educational-Development Workplace (33)	3D objects like cylinders	Virtual simulation, visualization	MS SQL Server database, OPC UA, Unity (3D),	Emphasizing interactive education and ease of configuration testing
Production Line (34)	Scripts, 3D objects, bidirectional communication	Troubleshooting, simulation, hands-on learning	Unity (3D), OPC UA	Practical method for learning FP systems using Game4Automation
Hydraulic System - Detecting Leaks (35)	Measurements in real-time, EPANET model, IoT microcontrollers	Remote monitoring, control, and leak diagnosis	EPANET, IoT, OPC UA	The application pertains to the real-time detection and identification of leaks in water distribution networks
Rolling Mill Coilers (36)	Virtual commissioning, Object-oriented DT	Testing, prototyping, commission-ing	Simulation models	Gain valuable insights into DT' many uses in hydraulic subsystem design and performance optimization
Closed Hydraulic System - Linear Actuator (37)	Condition monitoring, simulation model	Adaptability, scalability, reduced data collection	Data-driven approach, cyber-physical system	Showing how DT may train condition monitoring algorithms for adaptability and scalability.
Predictive Maintenance and Fault Diagnostics (38)	The utilization of DT technology for problem diagnosis and predictive maintenance.	Fault diagnosis, predictive maintenance, expert advice	Five-dimensional model, user interface	Proposed hydraulic system fault diagnostic and predictive maintenance DT framework
Energy Efficiency - Hydraulic Systems (39)	The real-time evaluation of energy efficiency measures	The automatic detection of inefficiencies and the provision of real-time interaction	Real-time simulation models, and Expert system	DT for real-time energy efficiency detection and implementation

Advanced Physics-Based Modeling (40)	Real-time synchronization, and Physics-based models	Optimization, monitoring, predictive maintenance	Virtual sensors	Using virtual sensors and physics-based models to understand health and performance
Practical Training System (41)	Simulation	Optimization and training	Intelligent control systems, Human-machine interaction,	Simulation, monitoring, and optimization of hydraulic and pneumatic components using DT
Engine Block Manufacturing (42)	Simulation models, Real-time monitoring, visualization tools	Optimization, predictive analysis, remote monitoring	IoT (Internet of Things)	The utilization of sophisticated monitoring techniques and predictive analysis
Smart Manufacturing Systems (43)	Virtual representations	Assembly and integration, monitoring, validation	PLC, OPC-UA	Makes it easier to assemble, integrate, and test different hydraulic and pneumatic components smoothly
Mechatronic System (44)	Bidirectional data flow, Virtual commissioning, real-time monitoring	Optimization, control logic validation, testing	Virtual testing, real-time communicati on	DT are a useful tool for the control, monitoring, and optimization of hydraulic and pneumatic systems in the FP domain
Automation Line (45)	Virtual models, debugging	Education, training, distance learning	Virtual testing	Gives students the chance to perform virtual labs that are similar to those in the industry, which supports remote learning and facilitates programming practice
Geothermal Drilling System (46)	Virtual entity, real-time monitoring	Control, fault detection, monitoring	Siemens NX (MCD), PLC, OPC standards	Has the capacity to improve hydraulic system fault diagnostics and detection for increased dependability and efficiency
Elevator Security System (47)	Virtual model	Monitor, discover anomalies in real time	Machine learning, PLC, Siemens NX (MCD)	Shows potential for enhancing industrial environments' security, control, and monitoring
Parallel Robot Controlled (48)	Dynamic visualization, real-time data, IoT sensors	Commissioning, design, education	IoT	Provides a flexible and effective method for FP system design, commissioning, and training

Machine Tool (49)	Simulation, real-time data integration, physical modeling	Condition monitoring, design space exploration	Models for collision detection, data visualiza-tion tools	DT are a vital resource for FP systems performance optimization, safety enhancement, and remote monitoring
Reconfigurable Assembly System (50)	Comprehensive system modeling and simulation	Condition monitoring, design space exploration	Model-based Approaches	Virtual testbed for sophisticated real-world FP system optimization in terms of design, operation, and maintenance
Material Handling System (51)	Decision-support modules, simulation models	Data-driven decision-making, Real-time interaction	Cyber-Physical System, Advanced simulations	Use of DT in FP systems to improve manufacturing process efficiency and make data-driven decisions

Technical Challenges

Using DT in FPAs presents many technological challenges that demonstrate the complexity of this field (52). In Figure 3, these issues demonstrate the direction for future research and development, emphasizing the need for creative solutions. Lack of fluid system data, especially working fluid data, is a major issue. Data scarcity hinders the construction of precise digital copies for FP components, requiring creative solutions (52). Fluid dynamics complicates DT creation more than electromechanical drives. Unlike other components, FP components require extensive fluid dynamics analysis throughout production, commissioning, and maintenance. This complexity presents a substantial challenge that requires focused attention in the development of DT for FPAs (52). Fluid data assimilation into DT is a major challenge, requiring user-friendly systems. Real-time monitoring and evaluation of FP components throughout their life cycle adds technical complexity. In a dynamic and intricate FP environment, resilient methods for real-time modeling and assessment of systems within a DT are needed to achieve this goal (52). In FP systems, simplifying complexity and organizing data for planning is a technological problem. DT models should be used for future planning with inventive ways that streamline and improve information (52). Hydraulic systems provide technical challenges. The measurement of time-varying parameters directly during operation is difficult due to parameter uncertainty and invisibility. Intrusive measurements are limited by the hydraulic component's sealed and integrated construction. Thus, non-invasive output measures matter (53). Real-time applications like predictive maintenance complicate hydraulic system modeling, which involves multi-physics interactions (53). Optimization is more complicated without parameter data and requires artificial intelligence/machine learning (53). Multi-scale dynamics in hydraulic systems and data availability and quality concerns complicate DT creation (53). DT adds complexity to big data systems, posing questions about how they interact with machine learning. Precision methods are needed to evaluate DT in FP systems. This requires quantitative comparisons to improve evaluation reliability (54). Modeling and data use must be precise to build DT throughout their life cycle, test them in real industrial sectors, and use artificial intelligence for decision-making (55). Standardizing communication interfaces, integrating cyber-physical systems, and standardizing procedures underline the need for a holistic approach (55).

Figure 3: Technical Challenges in Implementation of DT for FPA

Application of manufacturing system issues to FPAs reveals distinct challenges (56). Seamless bidirectional links between physical and virtual domains, including sensor technologies, communication protocols, and database administration, are crucial (56). High-fidelity modeling, automated verification and validation, and data integration are needed to optimize FP system processes (56). FP models are difficult to build because complex system aspects make it difficult to apply industrial knowledge (57). This study focuses on data creation, management, real-time interaction, and physical-virtual synchronization (57). Implementation costs, interaction with present IT systems, and application scalability across various fields add complexity, requiring continual R and D (57).

In conclusion, DT in FPAs provides difficult technological hurdles that demand interdisciplinary methods and continual research of breakthrough technologies. These issues improve DT implementation in FP systems when addressed (58).

Overcoming Technical Challenges

The review paper further examines the efficient methods for overcoming the challenges and restrictions associated with DT in FPAs. In order to address the problem of data availability, it is necessary to build strong data collection frameworks and deploy sophisticated sensors to ensure thorough data acquisition. Promoting the sharing of data and collaboration among industry participants can facilitate the development of comprehensive data repositories, while the implementation of data governance standards will ensure the preservation of data quality and reliability (52). Implementing modular and scalable digital twin models helps simplify the process by reducing complexity (53). Applying sophisticated machine learning and artificial intelligence methods will automate and enhance the process of creating models while promoting interdisciplinary collaboration will harness the knowledge and skills from other fields to tackle intricate problems (55). It is necessary to install continuous monitoring systems in order to collect real-time data for evaluating performance (57). Additionally, consistent metrics and benchmarks should be developed to measure the success of DT deployments. Conducting regular audits and reviews can facilitate the identification of areas that need improvement and guarantee compliance with industry standards.

Seamless integration frameworks are crucial for incorporating fluid data from different sources into DT models. Utilizing established data formats and protocols guarantees compatibility between various systems while employing advanced data fusion techniques allows for the integration of fluid data with other pertinent datasets for thorough analysis. Investing in high-performance computer resources and partnering with academic and research organizations can enhance high-fidelity modeling by utilizing state-of-the-art modeling methodologies (56). Consistent verification and improvement of models are essential to uphold correctness and dependability. In order to tackle the intricacies of fluid dynamics, it is necessary to carry out fundamental research to improve comprehension across different applications and to create simplified yet precise models that can encapsulate the essential aspects of fluid dynamics (54). By integrating empirical data with computer simulations, the validity and precision of fluid dynamics models can be enhanced and verified (58).

Research Gaps

As academics have studied modeling, simulation, and control, DT for FPAs have advanced. As in any developing topic, there are still substantial gaps in the information that give opportunities for further research. These research gaps must be identified to direct scholars toward untapped potential and unknown challenges. This section discusses research gaps and recommends future directions.

Interoperability and Standardization: The following investigations should prioritize the development of industry norms and protocols to ensure smooth communication and compatibility among DT implementations. This will improve cooperation and knowledge sharing in a diverse DT environment.

Real-time implementation issues: Many DT methods focus on offline simulation and analysis. Real-time implementation requires fast and effective algorithms, reliable data communication, and seamless integration with physical systems with low latency. To enable DT implementation in real-time FPAs, further research should address these issues.

Multidisciplinary approaches: Interdisciplinary FPAs involve fluid dynamics, control theory, mechanical engineering, and electrical systems. Current research often focuses on specific topics, avoiding field integration. To better represent FP systems, future research should create broad DT models that contain domain synergies and interdependencies.

Quantify uncertainty and analyse sensitivity: Uncertainties linked to parameters, operating circumstances, and external factors must be considered to accurately estimate FP system dynamics. Quantifying uncertainty and sensitivity analysis in DT models should be the focus of future study. This will help us understand system behaviors in diverse settings and assure more accurate data.

Advanced machine learning integration: Some research has used machine learning (ML) approaches in DT models for FP systems, although complex ML algorithms have not been thoroughly investigated. Deep learning, reinforcement learning, and other complex machine learning methods may be used to improve DT accuracy and flexibility in forecasting system behavior and optimizing FPAs.

Benchmarking and validation: Verifying FP DT models remains a major challenge. Standardized validation techniques and benchmarking criteria for DT methodology precision and dependability need more study. This simplifies model comparison and improves DT calculations.

Overall, the identified research gaps and potential areas for further research show that the DT sector for FPAs is ever-changing. Addressing these issues can help researchers create robust, precise, and transdisciplinary DT solutions. This will spur innovation and enable FP technology applications using DT.

This review paper makes a substantial contribution to the present knowledge of DT in FPAs by summarizing recent progress and discussing future possibilities. The review thoroughly addresses research gaps such as interoperability, standardization, and real-time synchronization problems, which are essential for the successful implementation of DT. The research additionally investigates particular instances of FPAs in which DT might augment predictive maintenance, optimize system performance, and promote overall operational efficiency in the industrial, automotive, and aerospace sectors. Furthermore, the review highlights areas of research where there is a lack of information, such as quality uncertainty, sophisticated machine learning algorithms, and the necessity for reliable benchmarking and validation methodologies. The paper's focus on addressing these gaps contributes to the advancement of scholarly knowledge and offers practical insights on how to effectively utilize DT technologies to improve the resilience and performance of FP systems in various industrial settings.

Conclusion

To summarize, this work has presented a thorough examination of the present applications, technical challenges, and areas of study that pertain to DT in FP systems. This paper emphasizes the significance of utilizing DT technology to improve efficiency, maintenance, and decision-making in fluid power engineering. It achieves this by examining current implementations and highlighting the potential advantages of implementing DT. The study highlights the significance of addressing real-time implementation challenges, which necessitate robust solutions due to the complex processing demands and the requirement for seamless integration with physical FP systems. The effective incorporation of DT into the complex domain of FP systems requires both acknowledging the potential advantages and taking a proactive stance in resolving related issues. The inclusion of information in this synthesis aims to strengthen current understanding and provide clarity on future directions, covering research areas such as the integration of advanced machine learning, the establishment of standardized validation procedures, and the important focus on quantifying uncertainty and analysing sensitivity.

Finally, integrating DT technology into FPAs advances the area. DT improve FP system efficiency through virtual replicas, real-time data analysis, and predictive modeling. This revolutionary technology could transform industrial maintenance, performance, and innovation. DT will become essential for FP engineering productivity and sustainability as they evolve. This study helps academics and professionals drive innovation and implementation in the dynamic field of DT for FPAs.

Abbreviation

Abbreviations used in this review are defined at their first occurrence in the manuscript.

AUV: Autonomous Underwater Vehicle
DT: Digital Twin
EHA: Electro-hydrostatic Actuators
EMA: Electromechanical Actuators
FP: Fluid Power
FPA: Fluid Power Application
IoT: Internet of Things
MCD: Mechatronics Concept Designer
ML: Machine Learning
PLC: Programmable Logic Controller
PID: Proportional-Integral-Derivative
SLR: Systematic Literature Review

Acknowledgement

Nil.

Author Contributions

All authors contributed equally to the conceptualization, literature synthesis, analysis, and interpretation of this review. All authors critically reviewed and approved the final manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest pertaining to this review paper.

Ethics Approval

This review publication did not require ethics approval because it did not collect new data from humans, animals, or experiments.

Funding

Nil.

References

1. Khamkar AD, Patil SM. Digital Twin in Fluid Power: Reviewing Constituents. International Research Journal of Multidisciplinary Scope (IRJMS). 2024 Jan 30;5(1):750–65.
2. Khamkar AD, Patil SM. Digital Twin in Fluid Power: Review-Technology Trends. International Research Journal of Multidisciplinary Scope (IRJMS). 2024 Apr 30;5(2):596–610.
3. Al-Hady IHA, Mohammed FM, Mohammed JAK. A review on the employment of the hydraulic cylinder for lifting purposes. Indonesian Journal of Electrical Engineering and Computer Science. 2022 Dec 1;28(3):1475–85.
4. Xu B, Shen J, Liu S, Su Q, Zhang J. Research and Development of Electro-hydraulic Control Valves Oriented to Industry 4.0: A Review. Chinese Journal of

Mechanical Engineering (English Edition). 2020 Dec 1;33(1):29.
5. Sénac T, Lelevé A, Moreau R, Novales C, Nouaille L, Pham MT, et al. A review of pneumatic actuators used for the design of medical simulators and medical tools. Multimodal Technologies and Interaction. 2019 Sep 1;3(3):47.
6. Foit K, Banaś W, Ćwikła G. The pneumatic and electropneumatic systems in the context of 4 th industrial revolution. In: IOP Conference Series: Materials Science and Engineering. Institute of Physics Publishing; 2018.
7. Qiao G, Liu G, Shi Z, Wang Y, Ma S, Lim TC. A review of electromechanical actuators for More/All Electric aircraft systems. In: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. SAGE Publications Ltd; 2018. p. 4128–51.
8. Zhang Q, Kong X, Yu B, Ba K, Jin Z, Kang Y. Review and development trend of digital hydraulic technology. Applied Sciences (Switzerland). 2020 Jan 1;10(2):579.
9. Scheidl R, Linjama M, Schmidt S. Is the future of fluid power digital? In: Proceedings of the Institution of Mechanical Engineers Part I: Journal of Systems and Control Engineering. 2012. p. 721–3.
10. Li Y, Li R, Yang J, Yu X, Xu J. Review of Recent Advances in the Drive Method of Hydraulic Control Valve. Processes. 2023 Aug 24;11(9):2537.
11. Yang H yong, Pan M. Engineering research in fluid power: a review. Journal of Zhejiang University: Science A. 2015 Jun 15;16(6):427–42.
12. Dindorf R, Takosoglu J, Wos P. Review of Hydro-Pneumatic Accumulator Models for the Study of the Energy Efficiency of Hydraulic Systems. Energies. 2023 Sep 7;16(18):6472.
13. Xavier MS, Tawk CD, Zolfagharian A, Pinskier J, Howard D, Young T, et al. Soft Pneumatic Actuators: A Review of Design, Fabrication, Modeling, Sensing, Control and Applications. IEEE Access. 2022;10:59442–85.
14. Nishioka Y, Suzumori K, Kanda T, Wakimoto S. Multiplex pneumatic control method for multi-drive system. Sensors and Actuators, A: Physical. 2010 Nov;164(1–2):88–94.
15. Dudić S, Reljić V, Šešlija D, Dakić N, Blagojević V. Improving energy efficiency of flexible pneumatic systems. Energies. 2021 Apr 1;14(7):1819.
16. Corallo A, Del Vecchio V, Lezzi M, Morciano P. Shop floor digital twin in smart manufacturing: A systematic literature review. Sustainability (Switzerland). 2021 Dec 1;13(23):12987.
17. Quan Z, Ge L, Wei Z, Li YW, Quan L. A Survey of Powertrain Technologies for Energy-Efficient Heavy-Duty Machinery. In: Proceedings of the IEEE. Institute of Electrical and Electronics Engineers Inc.; 2021. p. 279–308.
18. Shah R, Ozcelik S, Challoo R. Design of a highly maneuverable mobile robot. In: Procedia Computer Science. Elsevier B.V.; 2012. p. 170–5.
19. Giangrande P, Madonna V, Sala G, Kladas A, Gerada C, Galea M. Design and Testing of PMSM for Aerospace EMA Applications. In: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society. IEEE; 2018. p. 2038–43.
20. Tota A, Galvagno E, Velardocchia M, Vigliani A. Passenger car active braking system: Model and experimental validation (Part I). In: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. SAGE Publications Ltd; 2018. p. 585–94.
21. Oksanen T, Linkolehto R. Control of four wheel steering using independent actuators. In: IFAC Proceedings Volumes (IFAC-PapersOnline). IFAC Secretariat; 2013. p. 159–63.
22. Wang H. Design of PLC-based hydraulic system for workpiece turnover. In: Procedia Engineering. 2011. p. 122–6.
23. Lin CY, Shen FC, Wu KT, Lee HH, Hwang SJ. Injection molding process control of servo-hydraulic system. Applied Sciences (Switzerland). 2020 Jan 1;10(1):71.
24. Lin MH, Renn JC. Design of a novel energy efficient hydraulic tube bender. In: Procedia Engineering. Elsevier Ltd; 2014. p. 555–68.
25. Du X, Zong C, Zhang B, Shi M. Design, Simulation, and Experimental Study on the Hydraulic Drive System of an AUV Docking Device with Multi-Degree Freedom. Journal of Marine Science and Engineering. 2022 Nov 1;10(11):1790.
26. Velineni P, Suresh J, Kumar CN, Suresh M. Design of Pneumatic Gripper for Pick and Place Operation (Four Jaw). International Research Journal of Multidisciplinary Technovation. 2020 Mar 25;2(2):1–8.
27. Oladapo BI, Balogun VA, Oyegoke S, Adeoye AOM, Ijagbemi CO, Afolabi SO, et al. Experimental analytical design of CNC machine tool SCFC based on electro-pneumatic system simulation. Engineering Science and Technology, an International Journal. 2016 Dec 1;19(4):1958–65.
28. Vinter MY, Kopytov SO, Kabanov IN, Skachkov AY. Virtual Simulation of the Locomotive Pneumatic System Working Process. In: Transportation Research Procedia. Elsevier B.V.; 2022. p. 884–94.
29. Dezaki ML, Hatami S, Zolfagharian A, Bodaghi M. A pneumatic conveyor robot for color detection and sorting. Cognitive Robotics. 2022 Jan 1;2:60–72.
30. Huy DQ, Viet Bac N, Dang Thang L, Van Hung P, Thang VT. Low Cost Design of High Performance Lift Assist Pneumatic Manipulator. International Journal of Emerging Technology and Advanced Engineering. 2020;10(8):1–5.
31. Prasad A, Gowtham M, Mohanraman S, Suresh M. Automatic Sorting Machine. International Research Journal of Multidisciplinary Technovation. 2020 Jan 25;2(1):7–12.
32. Fait D, Masek V, Cermak R. Using Digital Twins in Mechatronics and Manufacturing. In: ISMSIT 2022 - 6th International Symposium on Multidisciplinary Studies and Innovative Technologies, Proceedings. Institute of Electrical and Electronics Engineers Inc.; 2022. p. 434–8.

33. Pajpach M, Drahos P, Pribis R, Kucera E. Educational-development Workplace for Digital Twins using the OPC UA and Unity 3D. In: Proceedings of the 31st International Conference on Cybernetics and Informatics, K and I 2022. Institute of Electrical and Electronics Engineers Inc: 2022.
34. Balla M, Haffner O, Kučera E, Cigánek J. Educational Case Studies: Creating a Digital Twin of the Production Line in TIA Portal, Unity, and Game4Automation Framework. Sensors. 2023 May 1;23(10):4977.
35. Gómez-Coronel L, Santos-Ruiz I, Torres L, López-Estrada FR, Gómez-Peñate S, Escobar-Gómez E. Digital Twin of a Hydraulic System with Leak Diagnosis Applications. Processes. 2023 Oct 1;11(10):3009.
36. Gasiyarov VR, Bovshik PA, Loginov BM, Karandaev AS, Khramshin VR, Radionov AA. Substantiating and Implementing Concept of Digital Twins for Virtual Commissioning of Industrial Mechatronic Complexes Exemplified by Rolling Mill Coilers. Machines. 2023 Feb 1;11(2):276.
37. Pichler K, Foschum P, Haas R, Schwacke J. Data driven condition monitoring based on a digital twin for a linear actuator realized as a closed hydraulic system. In: Annual Conference of the PHM Society. 2022.
38. Wang L, Liu Y, Yin H, Sun W. Fault diagnosis and predictive maintenance for hydraulic system based on digital twin model. AIP Advances. 2022 Jun 1;12(6):065213.
39. Ioshchikhes B, Borst F, Weigold M. Assessing Energy Efficiency Measures for Hydraulic Systems using a Digital Twin. In: Procedia CIRP. Elsevier B.V.; 2022. p. 1232–7.
40. Aivaliotis P, Georgoulias K, Arkouli Z, Makris S. Methodology for enabling digital twin using advanced physics-based modelling in predictive maintenance. In: Procedia CIRP. Elsevier B.V.; 2019. p. 417–22.
41. Li Y, Bing Z, Zhao D, Zhu Y, Lai Z. D&R of Digital Twin-based Intelligent Control Practical Training System. In Association for Computing Machinery (ACM); 2023. p. 46–52.
42. Bambura R, Šolc M, Dado M, Kotek L. Implementation of digital twin for engine block manufacturing processes. Applied Sciences (Switzerland). 2020 Sep 1;10(18):6578.
43. Leng J, Zhou M, Xiao Y, Zhang H, Liu Q, Shen W, et al. Digital twins-based remote semi-physical commissioning of flow-type smart manufacturing systems. Journal of Cleaner Production. 2021 Jul 15; 306:127278.
44. Dosoftei CC. Simulation Power vs. Immersive Capabilities: Enhanced Understanding and Interaction with Digital Twin of a Mechatronic System. Applied Sciences (Switzerland). 2023 Jun 1;13(11):6463.
45. Eriksson K, Alsaleh A, Behzad Far S, Stjern D. Applying Digital Twin Technology in Higher Education: An Automation Line Case Study. In: Advances in Transdisciplinary Engineering. IOS Press BV; 2022. p. 461–72.
46. Osinde NO, Byiringiro JB, Gichane MM, Smajic H. Process modelling of geothermal drilling system using digital twin for real-time monitoring and control. Designs. 2019 Sep 1;3(3):1–12.
47. Gichane MM, Byiringiro JB, Chesang AK, Nyaga PM, Langat RK, Smajic H, et al. Digital triplet approach for real-time monitoring and control of an elevator security system. Designs. 2020 Jun 1;4(2):1–14.
48. Michalík R, Hrbček J, Janota A. Parallel robot controlled by plc and its digital twin. TransNav. 2021 Dec 1;15(4):867–71.
49. Guo M, Fang X, Hu Z, Li Q. Design and Research of Digital Twin Machine Tool Simulation and Monitoring System. The International Journal of Advanced Manufacturing Technology. 2023;124(11–12):4253–68.
50. Zhang L, Cai ZQ, Ghee LJ. Virtual Commissioning and Machine Learning of a Reconfigurable Assembly System. In: 2nd International Conference on Industrial Artificial Intelligence, IAI 2020. Institute of Electrical and Electronics Engineers Inc.; 2020.
51. Glatt M, Sinnwell C, Yi L, Donohoe S, Ravani B, Aurich JC. Modeling and implementation of a digital twin of material flows based on physics simulation. Journal of Manufacturing Systems. 2021 Jan 1;58:231–45.
52. Rückert M, Merkelbach S, Alt R, Schmitz K. Online life cycle assessment for fluid power manufacturing systems – challenges and opportunities. In: IFIP Advances in Information and Communication Technology. Springer New York LLC; 2018. p. 128–35.
53. Cui Z, Yue J, Tao W, Xia Q, Chen J, Wu C. Enabling High-fidelity Modeling of Digital Twin for Hydraulic Systems: KP-PSO Based Parameter Identification. In: International Conference on Advanced Robotics and Mechatronics (ICARM). Institute of Electrical and Electronics Engineers (IEEE); 2023. p. 663–8.
54. Park H, Easwaran A, Andalam S. Challenges in digital twin development for cyber-physical production systems. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). Springer Verlag; 2019. p. 28–48.
55. Juarez MG, Botti VJ, Giret AS. Digital twins: Review and challenges. Journal of Computing and Information Science in Engineering. 2021 Jun 1;21(3):030802.
56. Ugarte-Querejeta M, Etxeberria L, Sagardui G, Unamuno G, Bediaga I. Virtual commissioning in machine tool manufacturing: A survey from industry. Dyna (Spain). 2021;96(6):612-619.
57. Tao F, Zhang M, Nee AYC. Digital Twin Shop-Floor. In: Digital Twin Driven Smart Manufacturing. Elsevier; 2019. p. 85–110.
58. Tao F, Zhang M, Nee AYC. Digital Twin-Driven Prognostics and Health Management. In: Digital Twin Driven Smart Manufacturing. Elsevier; 2019. p. 141–67.